IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 8, Issue 3 Ser. II (May – June 2020), PP 01-10
www.iosrjournals.org

Detecting Karst Collapses of Limestone Coalbed in Datong coal fields (China) using a comprehensive geophysical method

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Abstract: *This paper presents the application of comprehensive geophysical methods to the exploration of the coalbed floor limestone via a case study in the Datong coalfield. 3D Seismic Technology is applied to effectively detect the water-rich area of underground karst structure and ensure the safety of coal mine production. In the Carboniferous coal seam of Datong coalfield, the comprehensive geophysical methods,including surface 3D Seismic and CSAMT exploration, can effectively detect the water rich area of underground karst structure, effectively guide the safe production of coal mine, and has the prospect of popularization and application. The methods can also provide a reference for similar coal mines in China and other countries.*

Keywords: *Geophysical methods; Underground limestone Karst; Carboniferous coalbed; 3D seismic technology*

Date of Submission: 14-05-2020 Date of Acceptance: 29-05-2020

I. Introduction

Datong coalfield is located in the north of Shanxi Province, China, which is rich in coal resources. It is a Jurassic and Carboniferous-Permian coal seams [1-3]. It is a coal syncline with a strike of northeast, a tightening in the southwest and an opening in the northeast. It is about 85km long in the south-north, 30km wide in the east-west, and an area of $1827km^2$. Among them, the lower Carboniferous-Permian coal area is about $1739km^2$, and the upper Jurassic coal area in the north-east is about $700km^2$, overlapping 6 00 km^2 [4-6].

The upper Jurassic Coalfield has a long history of mining, and its resources are nearly exhausted. Since 2000, Datong coal field (north area) has gradually extended from Jurassic coal field to Carboniferous Permian coal field. At present, Tashan and other large-scale mines have been built, mainly mining coal seams 3-5 of Carboniferous system, Panjiayao and other Carboniferous system mines are also under construction.

The strata of the Datong coalfield consist of the Jining Rock Group (basement gneiss), Cambrian (limestone), Ordovician (limestone), Carboniferous (terrigenous clastic rock), Permian (terrigenous clastic rock), Jurassic (terrigenous clastic rock), Cretaceous (terrigenous clastic rock) and quaternary systems [7-9].

Under the Carboniferous coal seam floor in Datong coalfield, there is a huge thickness of Cambrian-Ordovician carbonate rocks (300-600). The problem of mining under pressure of karst water exists in the mining of Carboniferous coal seam in different degrees in each mine, and there is a threat of water inrush from the karst-fissure water in the floor, which seriously affects the safe production of the coal mine.

Therefore, it is urgent to find out the effective technical means to find out the development law of karst-fissure water in Datong coal field and the water-resisting layer of main coal seam floor in carboniferous system, accurately evaluate the risk zoning of water inrush in Datong coal field, formulate scientific and effective technical measures for mine water prevention and control [10-14], and provide reliable technical guarantee for the safe production of coal mine.

II. Study Area and Geophysical Characteristics

2.1. Electrical characteristic

In theory, the resistivity of dry rocks, less metamorphic coal and air is relatively high, but in practice the pores and cracks in rocks always contain water, and the resistivity drops sharply as the humidity or saturation of rocks increases. The resistivity of different rocks with the same water content is different because of the different salinity of water. Generally speaking, the resistivity of water-bearing structure is far less than that of water-free fault and water-free surrounding rock, which is the physical basis for the evaluation of water-bearing structure and water accumulation area [16-18] by electric method.

The corresponding resistivity of different rock strata varies with the change of lithology, and it varies greatly in the longitudinal (depth) direction. According to the statistics of borehole logging data in Datong mining area, the main electrical characteristics of rock strata are shown in Table 1.

Table 1: Electrical characteristics of coal strata.

lithology	Apparent resistivity Ω.M	Mean value	lithology	Apparent resistivity Ω.M	Mean value
loess	10-30	15	coarse-grained sandstones	80-170	120
Medium sandstone	60-130	100	Fine-grained sandstone	40-120	80
Siltstone	30-100	60	Mudstone	25-35	30
Coal seam	106-810	200	Limestone	400-1500	800
gneiss	90-130	110	Lamprophyre	1500-3000	1700

In Datong area, the resistivity of Jurassic coal measure strata (0-300m thick) is about 100 Ω. M, that of Carboniferous Permian coal measure strata (200-300m thick) is about 150 Ω. M, that of Cambrian Ordovician limestone (0-600m thick) is about 400-700 Ω. M, and that of gneiss basement is about 100 Ω. M. Therefore, there is a geophysical basis for using electrical exploration technology to find water-bearing structures [19-21].

2.2. Elastic characteristic

According to the statistics of borehole logging data in Datong mining area, the main elastic characteristics of rock strata are shown in Table 2.

Table 2: Elastic characteristics of coal strata.

lithology	P-wave speed M/S	Density g/cm3	lithology	P-wave speed M/S	Density g/cm3
loess	100-300	1.5	coarse-grained sandstones	3800	2.6
Medium sandstone	3800	2.4	fine-grained sandstone	3500	2.4
Siltstone	3300	2.4	Mudstone	2400	2.0
Coal seam	2000	1.5	Limestone	4000	3.0
gneiss	4000	2.8	Lamprophyre	4000	3.8

The conditions for the formation of reflection wave are that there must be wave impedance difference between coal seam and surrounding rock. The density of coal seam and seismic wave propagation velocity are significantly lower than that of surrounding rock (around 1:2), and the reflection coefficient of coal seam top and bottom interface can be as high as 0.15-0.5, or even higher; the main coal seam is generally a strong reflection layer with stable thickness and good continuity, and the coal seam is a typical thin layer, whose top and bottom interfaces form a good composite wave.

III. Comprehensive geophysical methods

3.1. CSAMT(Controlled Source Audio Magnetotelluric method)

CSAMT method is an artificial source frequency sounding method developed on the basis of AMT method, and its frequency range is 0.125 ~ 8192Hz. Since the frequency range, field intensity and direction of the electromagnetic field observed by CSAMT method can be controlled manually, and its observation mode is the same as that of AMT method, it is called Controlled Source Audio Magnetotelluric method.

Based on the electromagnetic wave propagation theory and Maxwell's equations, CSAMT derived the electric field and magnetic field formulas of horizontal electric dipole source on the ground:

$$E_x = \frac{I \cdot AB \cdot \rho_1}{2\pi^3} \cdot (3\cos^2\theta - 2) \quad (1)$$

$$E_y = \frac{3 \cdot I \cdot AB \cdot \rho_1}{4\pi^3} \cdot \sin 2\theta \quad (2)$$

$$E_z = (i-1)\frac{I \cdot AB \cdot \rho_1}{2\pi r^2} \cdot \sqrt{\frac{\mu_0 \omega}{2\rho_1}} \cdot \cos\theta \quad (3)$$

$$H_x = -(1+i)\frac{3I \cdot AB}{4\pi^3} \cdot \sqrt{\frac{2\rho_1}{\mu_0 \omega}} \cdot \cos\theta \cdot \sin\theta \quad (4)$$

$$H_y = (1+i)\frac{I \cdot AB}{4\pi^2} \cdot \sqrt{\frac{2\rho_1}{\mu_0 \omega}} \cdot (3\cos^2\theta - 2) \quad (5)$$

$$H_z = i\frac{3I \cdot AB \cdot \rho_1}{2\pi \mu_0 \omega r^{-4}} \cdot \sin\theta \quad (6)$$

Where *I*is the power supply current intensity; AB is the length of the power supply dipole; R is the distance between the field source and the receiving point.

By comparing the electric field (Ex) in the x direction of equation (1) with the magnetic field (Hy) in the y direction of equation (5), and through some simple calculations, the underground apparent resistivity (s) formula can be obtained:

$$\rho_s = \frac{1}{5f}\frac{|E_z|^2}{|H_y|^2} \quad (7)$$

Where f stands for frequency. As can be seen from equation (7), as long as two orthogonal horizontal electromagnetic fields (Ex, Hy) can be observed on the ground, the apparent resistivity s of the ground, namely Cagniard resistivity, can be obtained.

According to the skin effect theory of electromagnetic wave, the skin depth formula is derived:

$$H \approx 356\sqrt{\frac{\rho}{f}} \quad (8)$$

Where H stands for depth of exploration, ( ) for surface resistivity, and f for frequency.

According to formula (8), when the surface resistivity is fixed, the propagation depth (or detection depth) of electromagnetic wave is inversely proportional to the frequency. At high frequency, the detection depth is shallow; at low frequency, the detection depth is deep. The sounding depth can be changed by changing the transmitting frequency to achieve the purpose of frequency conversion sounding.

In the exploration area, the V8 -- 6R, Rxu -- 3ER multi-functional receiver and Txu -- 30 transmitter produced by Phoenix Corporation of Canada are adopted, and the generator is MG-30 generator set. The CSAMT-PRO processing system is adopted for CSAMT processing. The variation of primary field potential and magnetic field intensity is observed, and the difference of rock conductivity is studied to detect the karst development of limestone in coal-measure floor of the coalfield.

Device: The field device of CSAMT method includes field source and measuring station. The length of AB dipole source is 1.5km. The two ends of the dipole are connected to the aluminum foil buried in the pit, and the electrode is completely watered around with water to improve the electric coupling between the electrode and the earth. The measuring line in the measuring area is distributed in the far field, generally 6 ~ 8km away from the field source. The electric field Ex parallel to the field source and the magnetic field Hy perpendicular to it are measured. The electric field is observed by using a 20m long dipole (measuring electrode). The two ends of the dipole are connected to an unpolarized electrode in a pit wet with water.

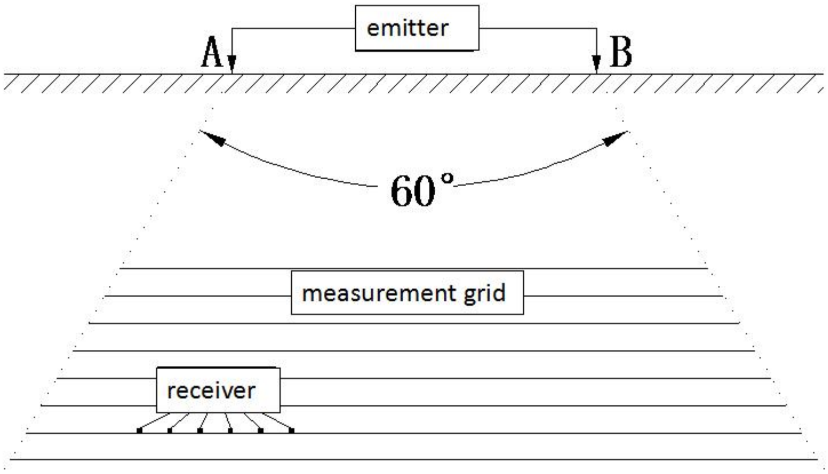

Figure 1: Working principle diagram of CSAMT method.

From the geological section of Datong coalfield, it can be known that the coal measure strata are 200-600 meters thick, and the Ordovician and Cambrian strata are 400-700 meters thick. Therefore, the sounding section depth is selected as 1200-1500 meters, so as to better identify the water-rich [22, 23] characteristics of coal seams, Ordovician and Cambrian aquifers. However, there are some issues to be considered as below:
(1) The mine area ground electricity interference is large;
(2) The terrain of the exploration area is complicated;
(3) The detection target size is relatively small;
For these reasons, the corresponding measures need to be taken:
(1) Trying to choose the area with small interference for the measurements;
(2) Accurately measuring the elevation of each point and using software for terrain compensation;
(3) Combining geological data of mining area and 3D Seismic results for fine interpretation;
Therefore, some main achievements can be found:
(1) By using CSAMT technique combined with the basic geological data of Datong coalfield, the resistivity characteristics and basic thickness of coal measure strata, limestone strata and gneiss basement can be determined;
(2) Different characteristics of the different tectonic CSAMT can be detected: the resistivity of water bearing fault and collapse column is obviously lower than that of surrounding rock, less than 80 Ω. M, especially the abnormality of water conducting collapse column on the limestone aquifer and the top of Ordovician limestone is obvious, which can effectively detect the water conducting channel and range, and guide the grouting filling structure;
(3) It is found that the basement structure of Datong coalfield is the main channel of lamprophyre intrusion, including the concealed basement structure of ShiliRiver in east-west direction, Kouquan fault in northeast direction, Qingciyao fault in northwest direction, and the secondary structure parallel to the above structure.
By applying CSAMT,some advantages can be summarized as:
(1) A large exploration depth: The current frequency range and possible transmission power of CSAMT's effective exploration depth range from tens of meters to 2-3km;
(2) High horizontal resolution: In general, the horizontal resolution of the artificial field method is not only restricted by objective factors (such as resistivity ratio), but also affected by the distance of transmitting and receiving and the size of receiving electric dipole. However, the horizontal resolution of CSAMT has nothing to do with the distance between transmission and reception. However, the horizontal resolution of CSAMT is independent of the transmitting and receiving distance, so it is roughly equal to the size of the receiving dipole.

(3) Good vertical resolution: The vertical resolution of a CSAMT depends on a number of factors. If the ratio of the thickness of a detectable object to its burial depth is defined as the vertical resolution, roughly speaking, it is 20% to 10%.
(4) Less impact of topography: Because of the normalization of the measured values during receiving, the terrain effect is relatively small, and because of the plane wave field, the terrain effect in the survey area is also small, and it is easy to correct.

3.2. 3D Seismic exploration structures

At present, the use of 3D Seismic exploration technology to detect geological structure and goaf location and scope of old kilns has been widely used in the field of coal exploration and engineering investigation, which is one of the necessary data for coal mine design and construction. However, the occurrence characteristics of the Datong double system coalfield and the exploration of the Lower Carboniferous coalfield structure under the condition of the Upper Jurassic mined-out bring great difficulties to 3D Seismic exploration technology. Because of the strong absorption of seismic wave energy in the goaf, the detection of lower coal in goaf is still a difficult problem in coal seismic exploration.However, there are some issues to be considered as below:
(1) The mountainous and hilly terrain in the exploration area is complex;
(2) The loess of the thick layer on the surface is not evenly covered and the shallow seismic geological conditions are poor;
(3) There are multi-layer goaf in the upper Jurassic;
For these reasons, the corresponding measures need to be taken:
(1) The seismic source adopts the combination of vibroseis and combined borehole gun;
(2) Three components, high coverage times and wide-angle reflection arrangement are selected for the observation system;
(3) The processing flow includes static comparison correction of different layers, comprehensive analysis of seismic multi-attribute, lithology analysis, etc.;
(4) The interpretation process adopts unified seismic multi-data volume and 3D visualization modeling technology.
3D Seismic data interpretation in the Datong coal mining area was explainedusing the workstation using full three-dimensional interactive interpretation software, data interpretation can be divided into tectonic interpretation, lithology interpretation, prediction and other aspects. There are dozens of traditional seismic attributes in time, amplitude, frequency, phase and absorption attenuation, and the multi-attribute joint analysis is also the development of seismic attribute analysis It is inevitable that the variance technique is one of the three-dimensional seismic attribute interpretation techniques of coal which has been widely used. The application of variance attribute greatly improves the efficiency and accuracy of structural interpretation.
Therefore, some main achievements can be found:
(1) Based on the basic theory of 3D Seismic exploration technology through goaf, the design method and data acquisition method of 3D Seismic exploration observation system through goaf are studied. The study focuses on the receiving and excitation methods and acquisition technology.
(2) The processing method of 3D Seismic exploration data passing through goaf is studied and a set of processing flow is formed. It focuses on the multi-attribute analysis methods (time, amplitude, frequency, phase and absorption attenuation, variance and other seismic properties).
(3) The interpretation method of 3D Seismic exploration through goaf is studied. The research focuses on 3D visual modeling.
By applying 3D Seismic exploration methods, some advantages can be summarized as:
(1) A large exploration scope and depth: With the continuous progress of static correction technology, 3D earthquakes in complex mountainous terrain, loess wall and desert areas can be effectively carried out. In Datong region, the influence of the upper Jurassic multi-layer goaf is particularly overcome, which provides technical support for the exploration of coal mine geological structure and hidden disaster investigation;
(2) Coal seam location, geological structure location is accurate. 3D seismic data visualization in combination with 3D visualization geological model building, able to depict a finer texture and structure distribution of coal seam, and provide detailed data for the preparation of the geological description [24, 25] of the mining area and the working face, especially the accuracy of the expected profile of the roadway provides reliable geological data for the design of the mining area and the support design of the driving working face.

IV. Results and Discussion

We have carried out comprehensive 3D Seismic exploration combined with CSAMT in several well fields of the Datong mining area, and achieved good results. In particular, karst water inrush risk survey in complex structure area has provided accurate geological data for mine safety production.

4.1 Comprehensive Exploration of Shuerligraben belt in MadaotouMine

The Madaotou well field is located in the southwest of the Datong coalfield syncline, and the Shuerligraben belt is located in the south of the well field. The general dip angle of the strata is 2-3°. It consists of a group of high-angle normal faults (Shuerli fault group) with a near east-west direction and a maximum fault distance of 290m. Due to the large fault drop, the coal seam and karst water have the damage of aquiclude, and the connected water may lead to water disaster.

The structure and water-bearing characteristics of the graben zone in Shuerli were ascertained by the comprehensive exploration technique of 3D Seismic exploration and CSAMT, which provided reliable data for the mining area design. Among them, 3D Seismic exploration and CSAMT joint exploration is a new combination of technology, which can effectively detect base structure, coal field boundary, coal field internal structure, structural water content and connectivity.

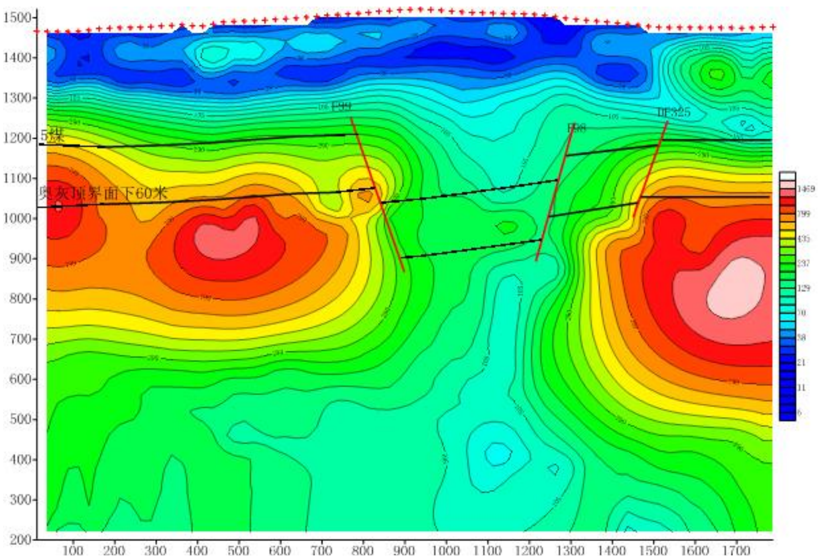

Figure 2: Combined 3D Seismic and CSAMT interpretation profile of L5 survey line in MadaotouMine.

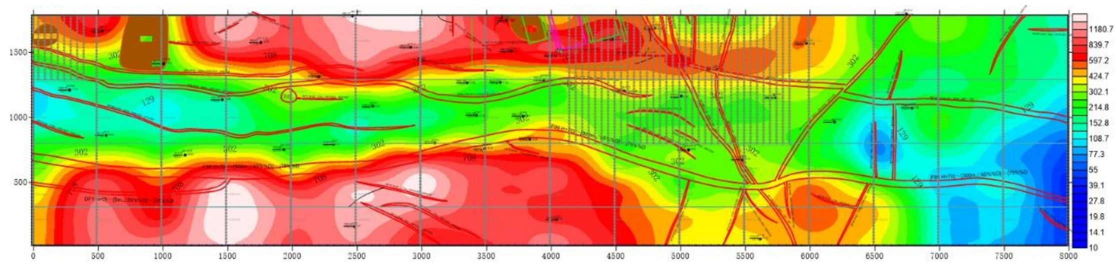

Figure 3: 3D Seismic and CSAMT joint interpretation plan of No. 5coal seam of L5 survey line in MadaotouCoal Mine.

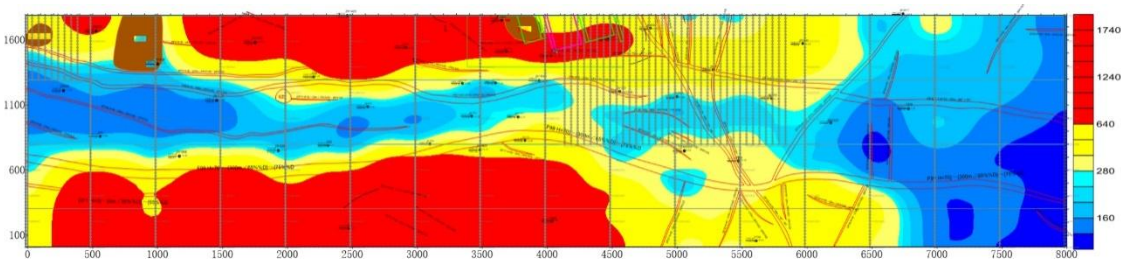

Figure 4: 3D Seismic and CSAMT joint interpretation plan of Ordovician limestone top interface in MadaotouCoal Mine.

3D Seismic exploration has identified the followings:

(1) Geological structure morphology and characteristics, formation occurrence and variation of the exploration area;

(2) Faults with a drop of more than 8 m in the exploration area, collapse columns with a diameter of more than 30 m, and igneous intrusions in coal seams with a scale of more than 30 m;

(3) Variation trend of strata, continuity and seam thickness of recoverable coal;
In comparison, CSAMT exploration has identified the followings:
(1) Distribution of groundwater in exploration areas;
(2) Hydraulic relationship between faults with a drop of more than 20m and Ordovician limestone water;
(3) The water-rich property of collapse column in 3D area;
(4) At the bottom of the coal measure strata, the strata with a depth of 60 meters are water-rich, and the abnormally water-rich area is defined.
Based on the comprehensive exploration, under the influence of Shuerligraben belt, the surface graben belt, and the northern area is located in the Yuanzi river basin with abundant surface water. No. 5 coal seam roof and floor were only rich in water in the eastern part of the exploration area, with strong connectivity with Ordovician limestone water, while other areas are poor in water; The Ordovician roof interface in graben zone has poor water-rich in the middle of exploration area, and strong water-rich in the west and east of exploration area, which is the key area for karst water control.

4.2 Comprehensive exploration in TashanCoal Mine

Tashan Coal Mine is located in the southeast of Datong coalfield, which is the first ten milliontonsof coal mine built by Tongmei group. On October 30, 2016, when lane 2228 in No.2 panel was tunneling to the position of 2300, water burst from the roadway floor, with a sudden water flow of about $200m^{\wedge 3}/h$. In order to find out the cause and channel of water inrush, and take effective measures to control it in time, 3D seismic exploration and CSAMT method were used to carry out comprehensive geophysical exploration in the area of 1.5 square kilometers in the No.2 panel area.

The buried depth of Cambrian and Ordovician is 700-800m, and the buried depth of C3-5 seam is 400-600m. The main aquifers in Cambrian and Ordovician are divided into upper and low aquifer rock groups: the lower Ordovician Liangjiashan and Zhili formation, and the upper Cambrian Fengshan formation two water-bearing rock groups.
3D Seismic exploration has identified the followings:
(1) Geological structure morphology and characteristics, formation occurrence and variation of the exploration area;
(2) The exploration area mainly develops NE-F1 reverse inference layer and conjugate NE-F2 (drop of 20 meters), NW-F3 (drop of 20 meters), S1 collapse column with a diameter of 400 meters and S2 collapse column with a diameter of 100 meters;
(3) Variation trend of strata, continuity and coal seam thickness of recoverable coal.
However, CSAMT can find out the following results:
(1) Groundwater distribution in the exploration areas;
(2) Hydraulic relationship among faults, collapse columns, and Ordovician limestone water;
(3) At the bottom of the coal measure strata, the strata with a depth of 60 meters are water-rich, and the abnormally water-rich area is defined.
Comprehensive analysis shows that the shallow area in the east of the survey area (1400m elevation range) is a low-resistivity and rich water area, which is the upper Jurassic small kiln drainage water area. In the intersection area of F1, F2, F3, and S1, the coal seam (1000m elevation range) and the lower limestone (800-900m elevation range) have the connectivity and low resistance area, which is the region of karst water through the structure. In the intersection area of F1 and S2, the coal seam (elevation range of 1000m) and the lower limestone (elevation range of 800-900m) are high resistivity regions, and the structure does not conduct karst water. The front right side of the water inrush point of the No. 2228 tunnel was exactly the location of the hydraulic connection with the Ordovician limestone water. Therefore, the detection area focuses on S1 collapse column area.

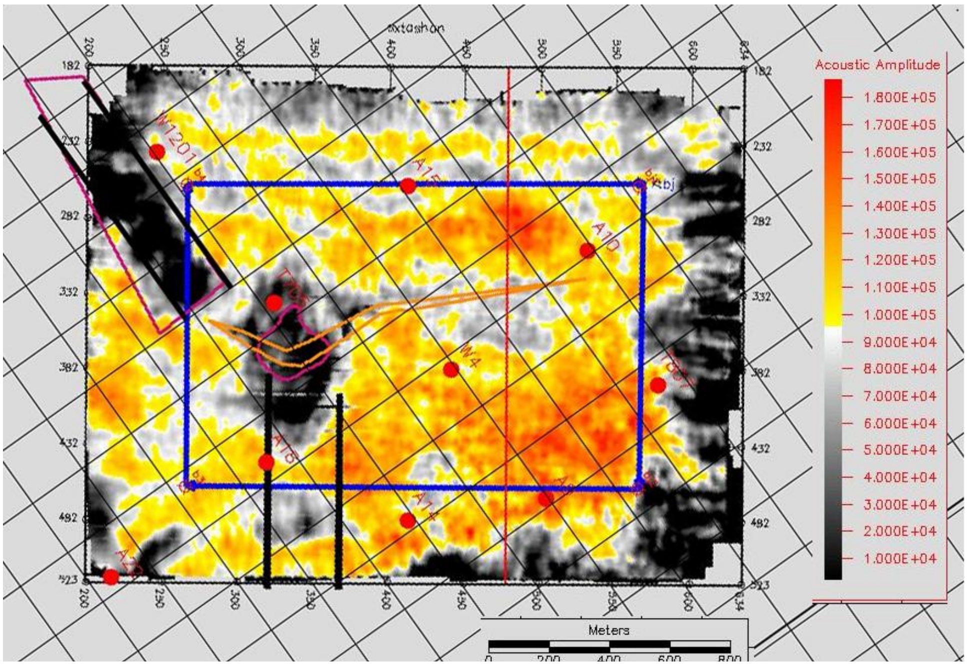

Figure 5: 3D Seismic interpretation structure plan of C3-5 coal seam of TashanCoal Mine.

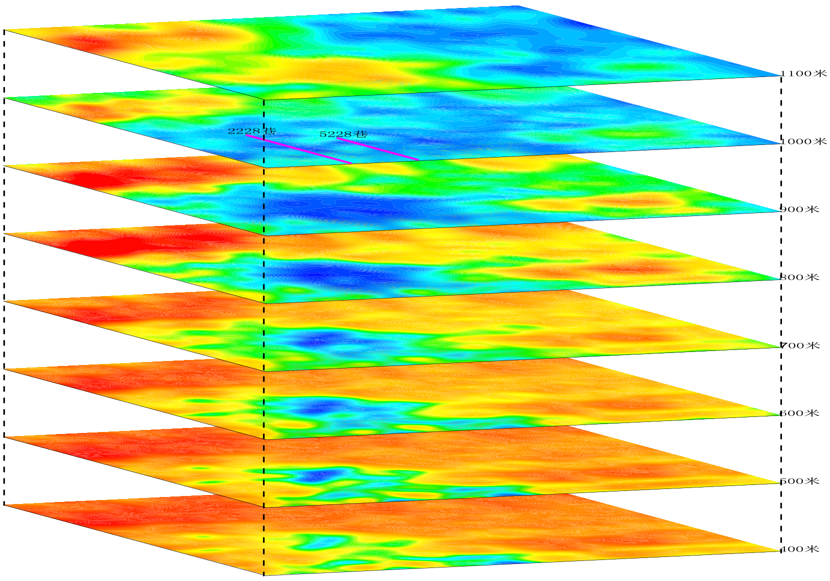

Figure 6: Plane slice of CSAMT interpretation structure in C3-5 coal seam of TashanCoal Mine.

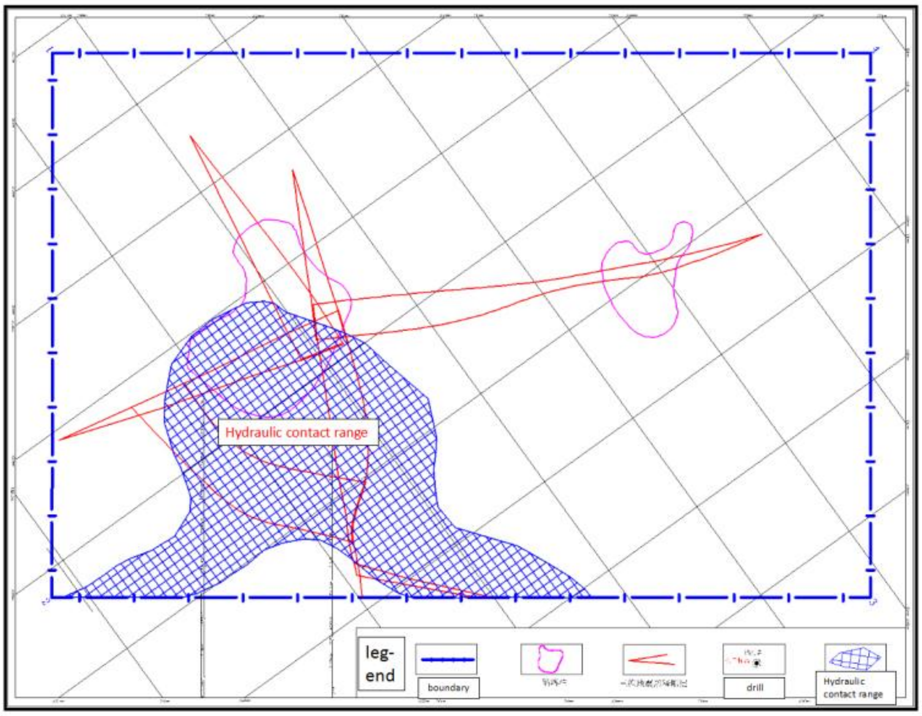

Figure 7: 3D Seismic and CSAMT comprehensive interpretation structure plan of C3-5 coal seam of TashanCoal Mine.

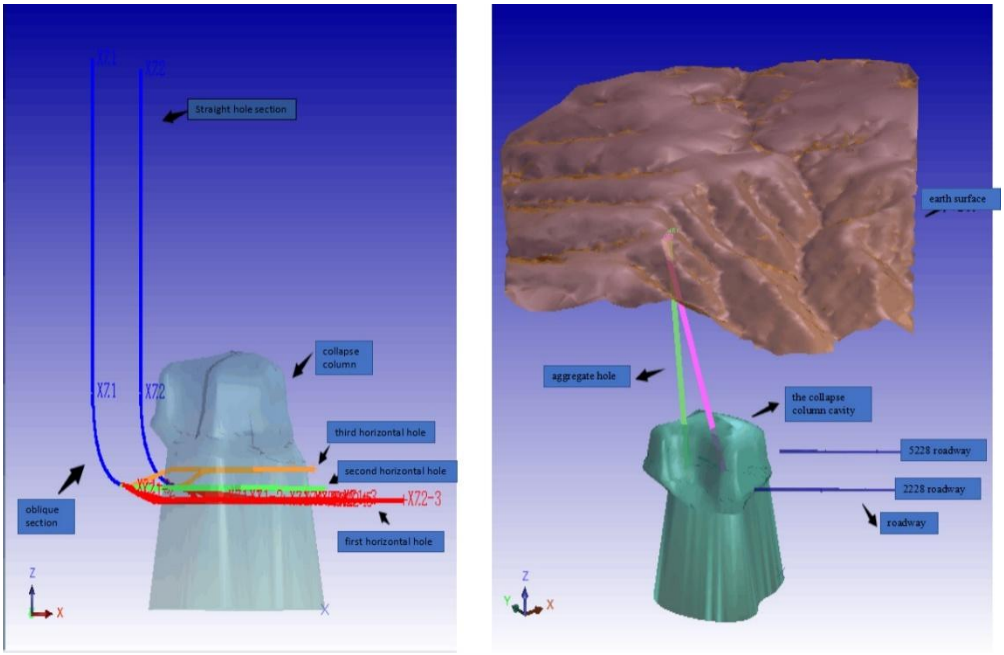

Figure 8: 3D map of collapse column treatment in C3-5 coal seam of TashanCoal Mine.

The results of the grouting treatment for the surface kilometer directional drilling:

(1) During the drilling of XZ1 and XZ2 grouting holes, the distribution of geological abnormal sections such as stratum breakage, serious leakage, drilling loss and no return of slurry is basically consistent with the distribution of ground 3D seismic and CSAMT exploration and interpretation water diversion collapse columns and faults, and the cement slurry injection reaches $70000m^3$.

(2) During the drilling of the XG2 aggregate hole on the top of the collapse column, several abnormal

situations such as severe slurry leakage, no return of slurry, accelerated penetration, drilling difficulties and so on occurred from 383m, reflecting that the impact of the collapse column caused the formation breakage and drilling difficulties. The drilling and borehole logging data showed that the elevation of the roof and floor of No. 3-5 coal seam was abnormal, and the overall strata decreased by about 25m. Abnormal gas gushing occurred in the borehole at 650m, and the borehole data as a whole reflected the development characteristics of the collapse column.

V. Conclusions

This paper presents the application of comprehensive geophysical methods to the exploration of the coalbed floor limestone via a case study in the Datong coalfield. 3D Seismic Technology is applied to effectively detect the water-rich area of underground karst structure and ensure the safety of coal mine production. In the Carboniferous coal seam of Datong coalfield, the comprehensive geophysical methods, including surface 3D Seismic and CSAMT exploration, can effectively detect the water rich area of underground karst structure, effectively guide the safe production of coal mine, and has the prospect of popularization and application. The methods can also provide a reference for similar coal mines in China and other countries.

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